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# Chapter 3—Principles of thermal comfort

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## 1. Introduction

The human body, considered as a thermodynamic system, produces mechanical work and low temperature heat, using food (fuel) and oxygen as input. This system requires, in healthy conditions, to maintain a constant internal temperature around $37 \pm 0.5°C$, otherwise the functionality of important organs like liver, spleen, etc, may be severely damaged.† In order to achieve this goal, the rate of heat generation of the body must be equal to the rate of heat loss from it. The job of our thermoregulatory system is to maintain the heat balance, that is a fundamental condition for survival and necessary (but not sufficient) for comfort. Skin temperature, otherwise, is not constant, and it varies according to the part of the body and the air temperature; the absolute maximum and the minimum values, however, are 45 and 4°C (pain thresholds).

## 2. Heat exchanges man–environment

The energy balance man–environment, per unit body surface area, may be written as follows:

$$S = M - W_k - E_{sk} - E_r - C - R - C_k \,[\mathrm{W\,m^{-2}}] \tag{1}$$

where $S$ = instantaneous energy balance of human body; $M$ = metabolic rate, i.e. internal heat production of the body; $W_k$ = external work; $E_{sk}$ = heat loss by evaporation from the skin; $E_r$ = respiration heat loss, latent and dry; $C$ = heat loss by

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† During heavy work it rises by a few tenths of degree; under extreme activity it may rise as high as 39.5°C for short durations; temperatures above 40°C maintained for many hours lead to a breakdown of the thermoregulatory system, causing death. Chilling of internal organs to 36°C is possible without damage; below this, muscular weakness, exposure and then death results. In carefully controlled situations, as in surgical hypothermia, 30°C can be reached.


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convection from outer surface of the clothed body to air; $R$ = heat loss by radiation from outer surface of the clothed body to its environment; $C_k$ = heat loss by conduction due to the contact skin/solid object.

All the terms of eqn (1) are expressed per unit area of body surface, thus allowing for people of different size and shape. A good estimate of the body surface area is given by the following expression (Dubois area, $A_{DU}$):

$$A_{DU} = 0.202 \cdot (w_b)^{0.425} \cdot (h_b)^{0.725}\ [\mathrm{m}^2] \tag{2}$$

where $w_b$ is the body weight (kg) and $h_b$ is the body height (m).

### 2.1. *Instantaneous energy balance*

The thermoregulatory system struggles to $S$ fluctuate around zero, with very small swings. When $S < 0$, the body is releasing more energy than it is producing, and its temperature tends to decrease. The first action of the thermoregulatory system is on skin thermal resistance, that is increased by means of the vasoconstriction mechanism; the blood vessels under the surface of the skin constrict. Vasoconstriction leads to a reduction of the blood flow and, consequently, to a reduction in the body surface temperature and in the rate of heat loss.‡

If this action is not sufficient, i.e. if still $S < 0$, our thermoregulatory system starts to act on energy production, by increasing it. First increasing the muscular tension, then, if still not enough, shivering occurs.

On the other hand, when $S > 0$, heat losses are not balancing heat production. The first action of the thermoregulatory system is to induce the vasodilatation; blood vessels expand, skin temperature increases and, with it, the heat loss rate. The overall effect is that of reducing the thermal resistance of the skin.

If the first action is not enough (i.e. still $S > 0$), sweating starts, involving larger and larger fractions of the body's surface area according to the extent of the inequality in the energy balance. Sweating improves evaporative heat losses.

### 2.2. *Metabolic rate*

Metabolic rate varies according to the activity performed; it is often measured in met (1 met = 50 kcal $\mathrm{h}^{-1}\,\mathrm{m}^{-2}$). In Table 1 some metabolic rates are given.

### 2.3. *External work*

External mechanical efficiency $\eta$ is defined as the ratio $W_k/M$, and ranges between 0 and 0.2; man, as an engine, is not very efficient. Legs are more efficient than arms.

‡ It is interesting to note that the formation of goose pimples, occurring at the extreme limit of vasoconstriction, is a useless action for today's physical characteristics of man. It was useful when we were very hairy all over the body surface; the raising of hairs was a good way to improve thermal insulation.

Table 1
Typical metabolic heat generation for various activities*

| Activity | Heat generation ($W\ m^{-2}$) |
|---|---|
| *Resting* | |
| Sleeping | 40 |
| Reclining | 45 |
| Seated, quiet | 60 |
| Standing, relaxed | 70 |
| *Walking (on the level)* | |
| $0.89\ m\ s^{-1}$ | 115 |
| $1.34\ m\ s^{-1}$ | 150 |
| $1.79\ m\ s^{-1}$ | 220 |
| *Office activities* | |
| Reading | 55 |
| Writing | 60 |
| Typing | 65 |
| Filing, seated | 70 |
| Filing, standing | 80 |
| Walking about | 100 |
| Lifting/packing | 120 |
| *Driving/flying* | |
| Car | 60–115 |
| Aircraft, routine | 70 |
| Aircraft, instrument landing | 105 |
| Aircraft, combat | 140 |
| Heavy vehicle | 185 |
| *Miscellaneous occupational activities* | |
| Cooking | 90–115 |
| House cleaning | 115–200 |
| Seated, heavy limb movement | 130 |
| Machine Work | |
| Sawing (table saw) | 105 |
| Light (electrical industry) | 115–140 |
| Heavy | 235 |
| Handling 50 kg bags | 235 |
| Pick and shovel work | 235–280 |
| *Miscellaneous leisure activities* | |
| Dancing, social | 140–225 |
| Calisthenics/exercise | 175–235 |
| Tennis, singles | 210–270 |
| Basketball | 290–440 |
| Wrestling, competitive | 410–505 |

* Most values are rounded; for example, the accrued value for a person seated, quiet, is $58.15\ W\ m^{-2}$.

### 2.4. *Heat loss by evaporation*

Heat loss by evaporation is made up of two terms, $E_d$ and $E_{sw}$. The former accounts for the heat loss by water vapour diffusion through the skin and it is not controlled by the thermoregulatory system. The latter accounts for the heat loss due to the regulatory sweat secretion from the skin and it is controlled by sweat glands.

$E_{sk}$ is a function of:

- air relative humidity, *rh*
- air temperature, $t_a$
- relative air velocity,§ $v_{ar}$
- skin temperature, $t_{sk}$
- clothing, including thermal resistance and vapour permeability, $I_{cl}$
- skin wettedness, i.e. fraction of the whole skin covered with a film of unevaporated sweat, *w*

### 2.5. *Respiration heat loss*

When breathing, expired air contains water vapour saturated at internal body temperature; the vaporization heat is taken from the lungs: this is the latent respiration heat loss. The other (dry heat loss) derives from the temperature difference between inspired and expired air. $E_r$ depends on:

- activity level
- air relative humidity
- air temperature

### 2.6. *Convective heat loss*

The convective heat flow rate from the body to the environment is given by:

$$C = f_{cl} h_c A_{DU}(t_{cl} - t_a)\,[\mathrm{W\,m^{-2}}] \tag{3}$$

where $f_{cl}$ = ratio of man's surface area clothed/nude; $h_c$ = average skin-air convective heat transfer coefficient; $t_{cl}$ = surface temperature of clothing; $t_a$ = air temperature.

*C* is a function of:

- air temperature
- average temperature of clothed body surface
- kind of clothing
- relative air velocity

§ Relative to the body; for example, for a person walking at 3 km h$^{-1}$ in absence of wind, the relative air velocity will be 3/3.6 = 0.83 m s$^{-1}$.

### 2.7. *Radiative heat loss*

The rate of radiative energy exchange between the human body and its environment may be expressed as:

$$R = 3.96 \times 10^{-8} f_{cl} A_{DU}[(t_{cl}+273)^4 - (t_{mr}+273)^4]\ [\mathrm{W\,m^{-2}}] \tag{4}$$

where the mean radiant temperature $t_{mr}$ is defined as the uniform blackbody temperature of an imaginary enclosure with which man exchanges the same heat by radiation, as he would in the actual complex environment, and can be calculated as:

$$t_{mr} = \sum t_i F_{p,i}\ [^\circ\mathrm{C}] \tag{5}$$

with $t_i$ = temperature of the generic isothermal surface $i$ seeing the subject (a wall, a window, piece of furniture, another person, etc.) $F_{p,i}$ = view (or angle) factor between the subject $p$ and the surface $i$; it may be evaluated by means of the procedure described in Appendix A.

$R$ is a function of:

- average temperature of clothed body surface
- mean radiant temperature
- kind of clothing

### 2.8. *Heat loss by conduction*

This is the loss occurring, when seated, as heat is exchanged between the body and the chair, or when standing as exchange between feet and floor. The term $C_k$ is difficult to evaluate: it is usually ignored as a separate item, but taken into account in the clothing thermal resistance.

### 2.9. *Thermal resistance of clothing*

The process of heat conduction through the clothing is quite complex, involving transfer through air spaces, conduction through solid material, which varies if wet, radiation exchanges between layers, etc. Because of the difficulties inherent in the handling of so many (and often impossible to determine) parameters, a simplification has been adopted, and the properties of clothing have been included in an overall thermal resistance. The new unit clo has been introduced, which is a dimensionless expression for the thermal insulation of clothing, measured from the skin to the outer surface of the clothes, but excluding the external surface resistance:

$$1\ \mathrm{clo} = 0.155\ \mathrm{m^2\,^\circ C\,W^{-1}}$$

that represents approximately the thermal resistance of a lounge suit with normal underwear.

Values of thermal resistance $I_{cl}$ of some typical clothing ensembles, expressed in

$m^{2\circ}C\ W^{-1}$ and in clo units, are given in Table 2. For clothing ensembles not included in Table 2, individual resistances of various garments are available in Table 3. The total resistance for the entire clothing ensemble is then determined by the sum $\Sigma I_{cli}$ and by using the equation $I_{cl} = 0.82\ \Sigma I_{cli}$.

## 3. Comfort indices

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment. Dissatisfaction may be caused by warm or cool discomfort for the body as a whole, but thermal dissatisfaction may also be caused by an unwanted heating or cooling of one particular part of the body (local discomfort).

### 3.1. *Effective temperature*

The Effective Temperature $ET^*$ is defined as the uniform temperature of an imaginary enclosure at 50% relative humidity in which a person exchanges the same total heat as in the actual environment; two environments with the same $ET^*$ should evoke the same thermal response even though they have different temperatures and humidity (but same air velocity).

Table 2
Values of typical clothing ensembles

| Clothing ensemble | $m^{2\circ}C\ W^{-1}$ | clo |
|---|---|---|
| Nude | 0 | 0 |
| Shorts | 0.015 | 0.1 |
| Typical tropical clothing ensemble (briefs, shorts, open neck shirt with short sleeves, light socks and sandals) | 0.045 | 0.3 |
| Light summer clothing (briefs, long light-weight trousers, open neck shirt with short sleeves, light socks and shoes) | 0.08 | 0.5 |
| Light working ensemble (light underwear, cotton work shirt with long sleeves, work trousers, woollen socks and shoes) | 0.11 | 0.7 |
| Typical indoor winter clothing ensemble (underwear, shirt with long sleeves, trousers, jacket or sweater with long sleeves, heavy socks and shoes) | 0.16 | 1.0 |
| Heavy traditional European business suit (cotton underwear with long legs and sleeves, shirt, suit including trousers, jacket and waistcoat, woollen socks and heavy shoes) | 0.23 | 1.5 |

Table 3
Individual insulation values of men's and women's garments

| Men | | Women | |
|---|---|---|---|
| Garment | $I_{cli}$ (clo) | Garment | $I_{cli}$ (clo) |
| Cool socks | 0.03 | Bra and panties | 0.05 |
| Warm socks | 0.04 | Pantihose | 0.01 |
| Briefs | 0.05 | Girdle | 0.04 |
| T-shirt | 0.09 | Half slip | 0.13 |
| Undershirt | 0.06 | Full slip | 0.19 |
| Woven s.s. shirt | 0.19 | Cool dress | 0.17 |
| Woven l.s. shirt | 0.29 | Warm dress | 0.63 |
| Cool s.s. knit shirt | 0.14 | Warm l.s. blouse | 0.29 |
| Warm s.s. knit shirt | 0.25 | Warm skirt | 0.22 |
| Cool l.s. knit shirt | 0.22 | Cool l.s. blouse | 0.20 |
| Warm l.s. sweater | 0.37 | Cool slacks | 0.26 |
| Warm jacket | 0.49 | Warm slacks | 0.44 |
| Cool trousers | 0.26 | Cool sleeveless sweater | 0.17 |
| Warm trousers | 0.32 | Warm l.s. sweater | 0.37 |
| Shoes | 0.04 | Cool s.s. sweater | 0.17 |

Note—s.s.: short sleeved; l.s.: long sleeved.

### 3.2. *Operative temperature*

The combined effects of air and mean radiant temperature can be combined into a single index, the operative temperature. The operative temperature $t_o$ is defined as the uniform temperature (i.e. equal values of $t_{mr}$ and $t_o$) of an imaginary enclosure in which man will exchange the same dry heat by radiation and convection as in the actual environment. For thermally moderate environments and for $t_{mr} - t_a < 4°C$, it may be assumed that $t_o = (t_{mr} + t_a)/2$.

### 3.3. *Skin wettedness*

The skin wettedness is the ratio of observed skin evaporation loss to the maximum; this index is considered as particularly suitable for predicting discomfort in hot environmental conditions.

### 3.4. *The predicted mean vote*

As previously noticed, a necessary condition for thermal comfort is the satisfaction of the energy balance of human body, i.e. the satisfaction of the condition $S = 0$ (see eqn (1)). Thus, taking into account the subjective variables and the environmental

Table 4
Thermal sensation scale used by Fanger

| | | |
|---|---|---|
| + | 3 | Hot |
| + | 2 | Warm |
| + | 1 | Slightly warm |
| | 0 | Neutral |
| − | 1 | Slightly cool |
| − | 2 | Cool |
| − | 3 | Cold |

ones, the thermal equilibrium of the body is satisfied if:

$$f(M, W, I_{cl}, t_a, rh, t_{mr}, t_{sk}, E_{sw}) = 0 \tag{6}$$

$$E_{sw} = 0.42\{(M-W)/A_{DU} - 58.15\}\,[\mathrm{W}] \tag{7}$$

$$t_{sk} = 35.7 - 0.0275(M-W)/A_{DU}\,[^\circ\mathrm{C}] \tag{8}$$

For example, a person seated, relaxed ($M/A_{DU} = 58.15$, $W_k = 0$, see Table 1) will experience comfort condition if [1]:

- thermal balance is satisfied (eqn (6))
- no sweating occurs ($E_{sw} = 0$, from eqn (7))
- average skin temperature is 34.2°C (from eqn (8))

It is very unlikely that subjective and environmental conditions are such that eqns (6)–(8) are simultaneously satisfied and, therefore, perfect comfort is experienced. Most likely sweating rate and/or average skin temperatures will be very close but not coincident with the comfort ones. In this case, how uncomfortable does a person feel?

In order to face this problem, Fanger [1] proposed a comfort index called Predicted Mean Vote (*PMV*). *PMV* is an index that predicts the mean value of the votes of a large group of persons on a seven-point thermal sensation scale (Table 4).

The *PMV* index can be determined when the activity (metabolic rate) and the clothing (thermal resistance) are estimated, and the following environmental parameters are measured: air temperature, mean radiant temperature, relative air velocity and partial water vapour pressure. The *PMV* is given by the equation:¶

$$\begin{aligned} PMV = {} & (0.303e^{-0.036M} + 0.028)\{(M-W) - 3.05\times10^{-3}[5733 - 6.99(M-W) - p_a] \\ & - 0.42[(M-W) - 58.15] - 1.7\times10^{-5}M(5867 - p_a) - 0.0014M(34\text{-}t_a) \\ & - 3.96\times10^{-8}f_{cl}[(t_{cl}+273)^4 - t_{mr}+273)^4 - f_{cl}h_c(t_{cl}-t_a)\} \end{aligned} \tag{9}$$

¶ In the *PMV* index the physiological response of the thermoregulatory system has been related statistically to thermal sensation votes collected from more than 1300 subjects.

where

$$t_{cl} = 35.7 - 0.028(M-W) - I_{cl}\{3.96\times10^{-8} f_{cl}[(t_{cl}+273)^4 - t_{mr}+273^4] + f_{cl}h_c(t_{cl}-t_a)\}$$

$$h_c = \begin{bmatrix} 2.38(t_{cl}-t_a)^{0.25} & \text{for } 2.38(t_{cl}-t_a)^{0.25} > 12.1(v_{ar})^{1/2} \\ 12.1(v_{ar})^{1/2} & \text{for } 2.38(t_{cl}-t_a)^{0.25} < 12.1(v_{ar})^{1/2} \end{bmatrix}$$

$$v_{ar} = v_a + 0.005(M/A_{DU} - 58.15)$$

$$f_{cl} = \begin{bmatrix} 1.00 + 1.290\cdot I_{cl} & \text{for } I_{cl} < 0.078\ \mathrm{m^{2\circ}C\,W^{-1}} \\ 1.05 + 0.645\cdot I_{cl} & \text{for } I_{cl} > 0.078\ \mathrm{m^{2\circ}C\,W^{-1}} \end{bmatrix}$$

where all terms have been previously defined, except $p_a$ = partial vapour pressure, in pascals.

The *PMV* index is derived for steady state conditions, but can be applied with good approximation during minor fluctuations of one or more of the variables, provided that time-weighted averages of the variables are applied.

It is recommended to use the *PMV* index only for values between $-2$ and $+2$ and when the six main parameters are inside the following intervals:

$M = 46 \div 232$ W m$^{-2}$ (0.8–4 met)
$I_{cl} = 0 \div 0.31$ m$^{2\circ}$C W$^{-1}$ (0–2 clo)
$t_a = 10 \div 30$ °C
$t_{mr} = 10 \div 40$ °C
$v_{ar} = 0 \div 1$ m s$^{-1}$
$p_a = 0 \div 2700$ Pa

The *PMV* may be determined either using a digital computer or directly from Appendix B, where graphs of *PMV* values vs operative temperature are provided for different activities, clothing and relative air velocities, with relative humidity kept constant and equal to 50%. The influence of humidity on thermal sensation, however, is small at moderate temperatures close to comfort and may usually be neglected when determining the *PMV* value.

### 3.5. *Predicted percentage of dissatisfied*

The *PMV* index predicts the mean value of the thermal votes of a large group of people exposed to the same environment, but individual votes are scattered around this mean value. In order to predict the number of people likely to feel uncomfortably warm or cold the Predicted Percentage of Dissatisfied (*PPD*) index has been introduced. The *PPD* index establishes a quantitative prediction of the number of thermally dissatisfied persons.

When the *PMV* value has been determined, the *PPD* can be found from Fig. 1 or determined from the equation:

$$PPD = 100 - 95\cdot exp[-(0.03353\cdot PMV^4 + 0.2179\cdot PMV^2)] \tag{10}$$

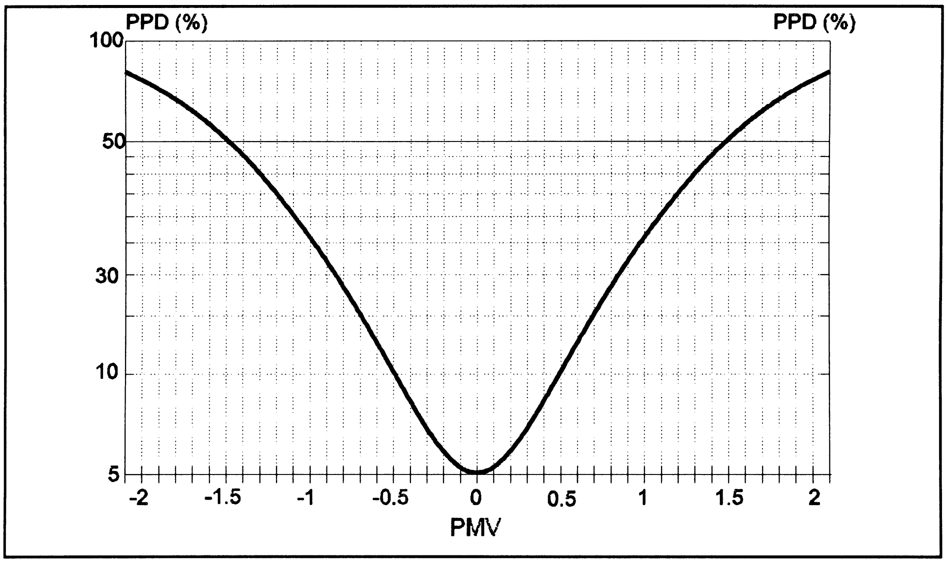



Fig. 1. Predicted percentage of dissatisfied (*PPD*) as a function of predicted mean vote (*PMV*).

Owing to individual differences it is impossible to specify a thermal environment that will satisfy everybody. This is highlighted in Fig. 1, where it is shown that even if the *PMV* is zero, 5% of people are dissatisfied. It is possible, however, to specify environments known to be acceptable by a certain percentage of the occupants. The ISO standard 7730 [2], for example, recommends that the *PPD* should be lower than 10%, i.e. *PMV* within the range $-0.5 \div \pm 0.5$.

## 4. The adaptation model

There is no significant difference in the thermal sensation of people who usually live in a very cold, hot or temperate climate when they are exposed to the same thermal environment. However, differences have been found in the neutral temperatures|| of occupants in buildings around the world. It has been found that comfortable indoor temperatures were related to the outdoor temperature, particularly in free running# buildings: the higher the latter the higher the former. This is not due to physiological differences but to differences of expectation. The adaptation model (Fig. 2), which takes into account such factors, may offer an alternative approach for predicting comfort in non air-conditioned buildings. People adapt by changing the physical parameters (environment), their physiology or activity level, their clothing, their

|| The ambient temperature found by statistical analysis to most frequently coincide with the central or optimal rating in a thermal comfort study. # Without any heating or air-conditioning system.

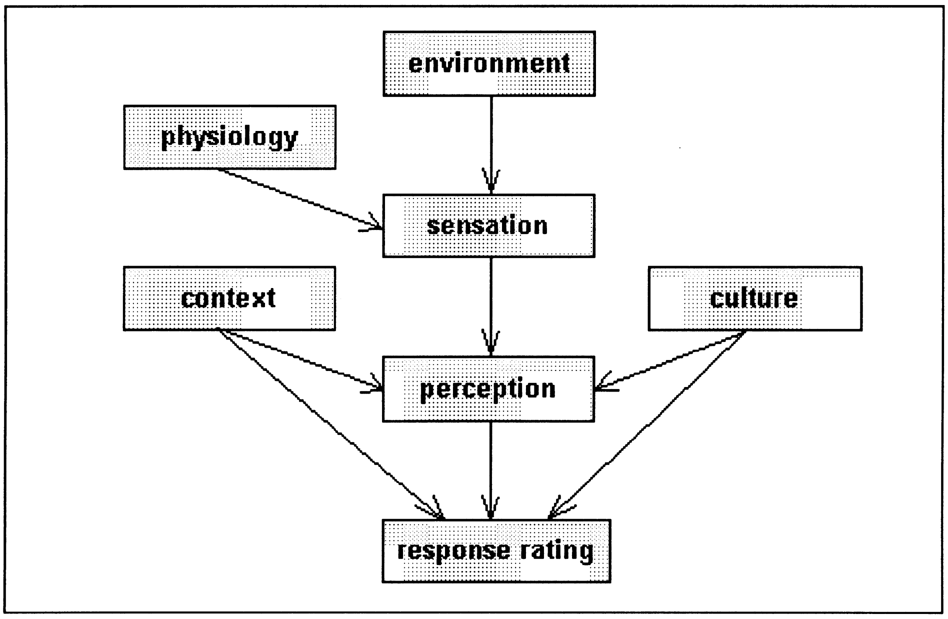



Fig. 2. The adaptation model.

expectations and the way they use rating scales. In simple deterministic terms the environment affects a person's sensation of that environment which in turn alters their perception and finally their assessment using a rating scale.

## Appendix A

*View factors between a person and an enclosure*

The view factor from $P$ to surface $\alpha$, $F_{P,\alpha}$, can be defined as the fraction of the diffuse radiant energy leaving the surface $\alpha$ which falls directly on $P$, (i.e. is intercepted by $P$); this implies that the larger is the apparent size of the surface $\alpha$, as seen by $P$, the larger is the view factor (Fig. A1).

Consider a person sitting or standing in a parallelepiped enclosure; with regard to the view factors, this enclosure can be divided in six different geometrical situations (Figs A2 and 3), in such a way that the person sees 24 rectangles as one, $\alpha$, depicted in Fig. A1. If symmetries are considered, the six situations can be reduced to four, as shown in Figs A4 and A5 for a seated person and in Figs A6 and A7 for a standing person.

To calculate the view factor $F_{P,i}$ from a person $P$ and a surface $i$, the following simplified and sufficiently accurate procedure can be used, with reference to Figs A4–A7, where:

Table A1
View factors

| Refer to | $F^*$ | $A$ | $B$ | $C$ | $D$ | $E$ |
|---|---|---|---|---|---|---|
| Fig. A4 | 0.118 | 1.21590 | 0.16890 | 0.71739 | 0.08733 | 0.05217 |
| Fig. A5 | 0.116 | 1.39569 | 0.013021 | 0.95093 | 0.07967 | 0.05458 |
| Fig. A6 | 0.120 | 1.24186 | 0.16730 | 0.61648 | 0.08165 | 0.05128 |
| Fig. A7 | 0.116 | 1.59512 | 0.12788 | 1.22643 | 0.04621 | 0.04434 |

$$F_{P,i} = F^*(1-\exp[-(a/c)/\tau]) \times (1-\exp[-(b/c)/\gamma]) \tag{A1}$$

$$\tau = A + B\frac{a}{c} \tag{A2}$$

$$\gamma = C + D + \frac{b}{c} + E\frac{a}{c} \tag{A3}$$

The values of the parameters $F^*$, $A$, $B$, $C$, $D$ and $E$ are given in Table A1 for seated and standing persons.

Since an additive property can be applied to view factors, in the case of a window, the view factor $F_{P,efgh}$ can be calculated as (Fig. A8):

$$F_{P,efgh} = F_{P,abcd} - F_{P,jgmd} - F_{P,keid} + F_{P,jhid}$$

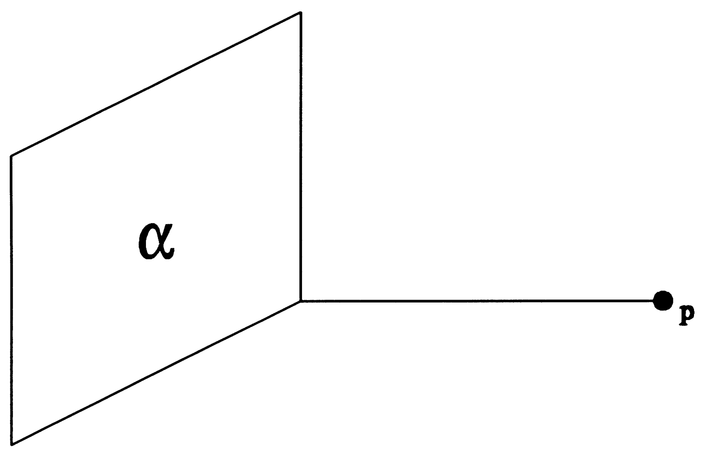



Fig. A1

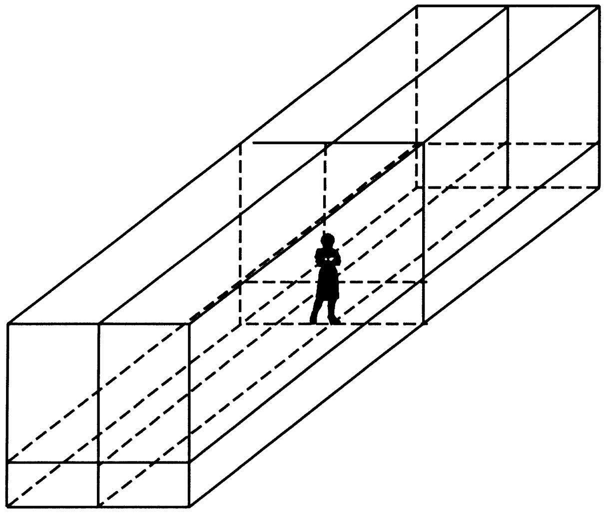


Fig. A2

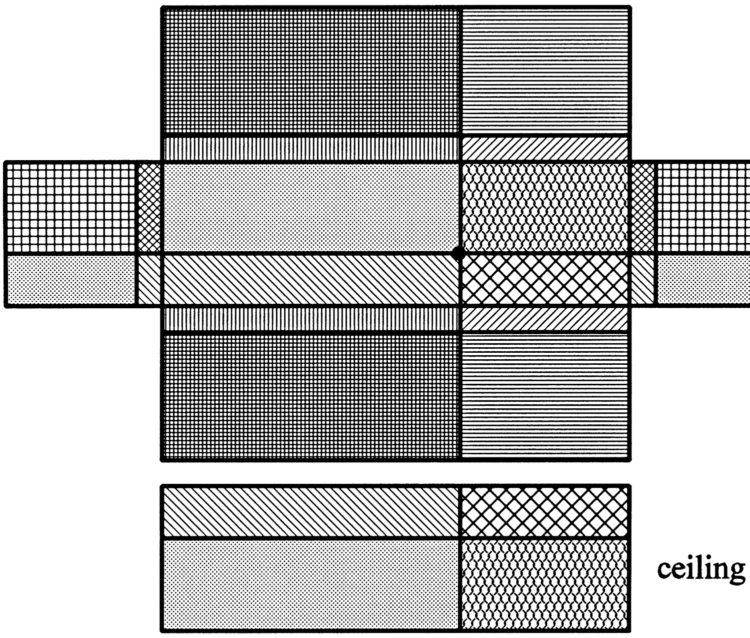



Fig. A3

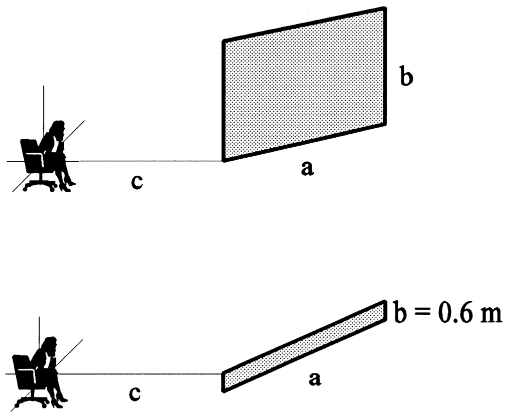



Fig. A4

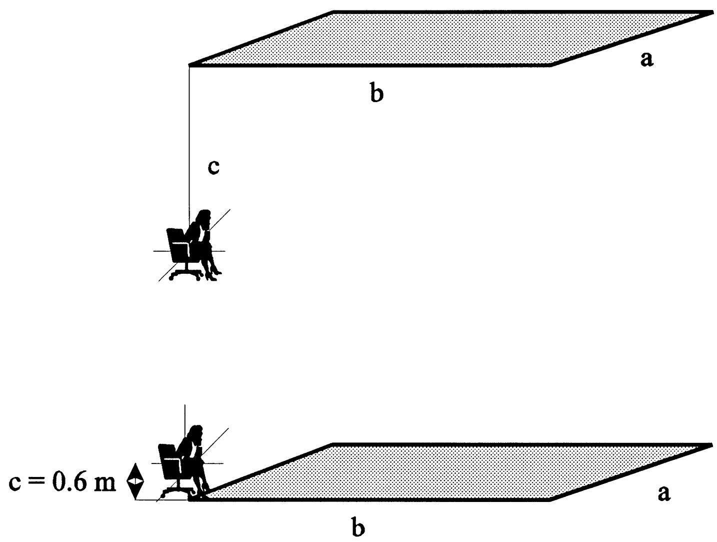



Fig. A5

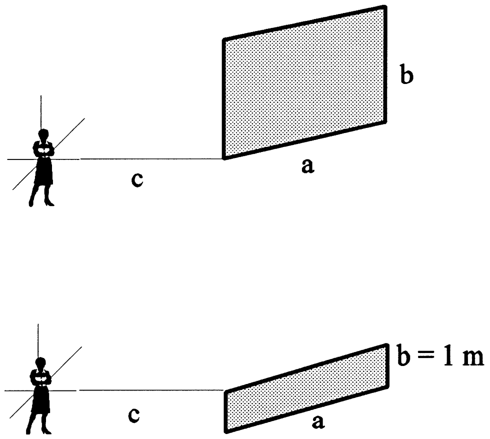



Fig. A6

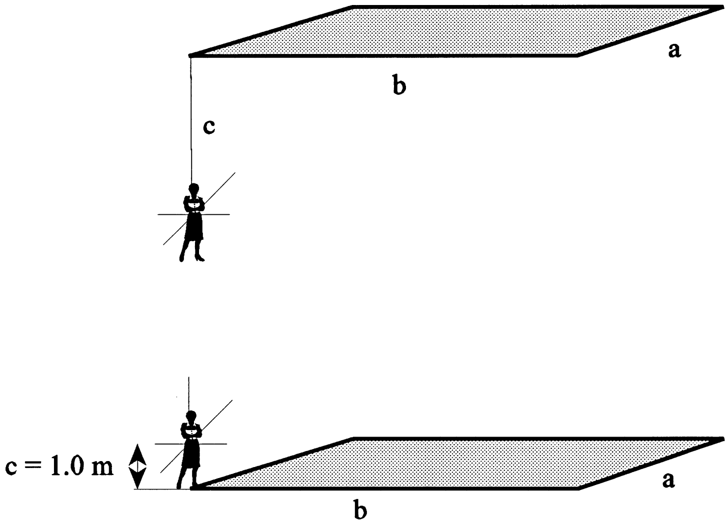



Fig. A7

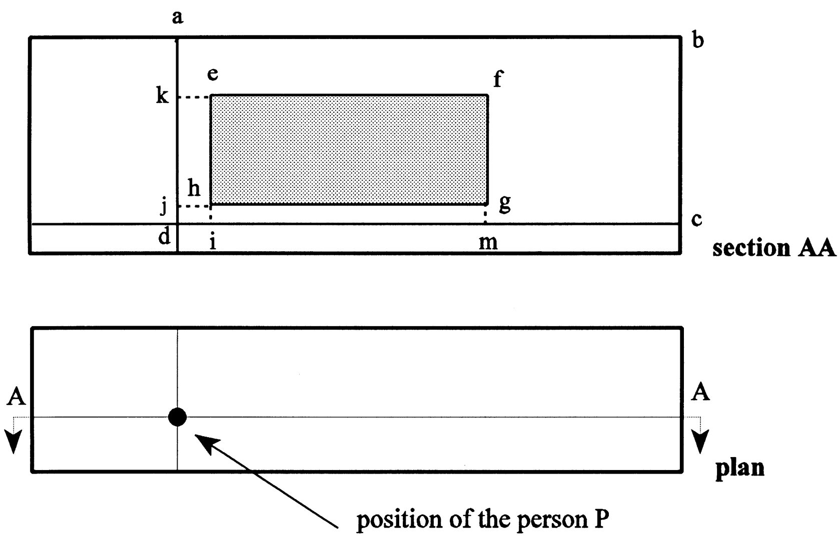



Fig. A8

## Appendix B

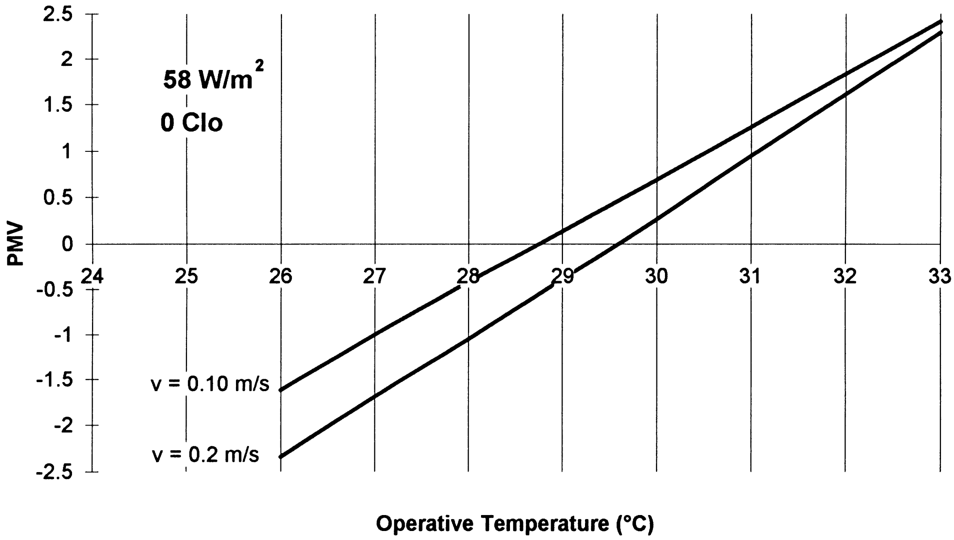
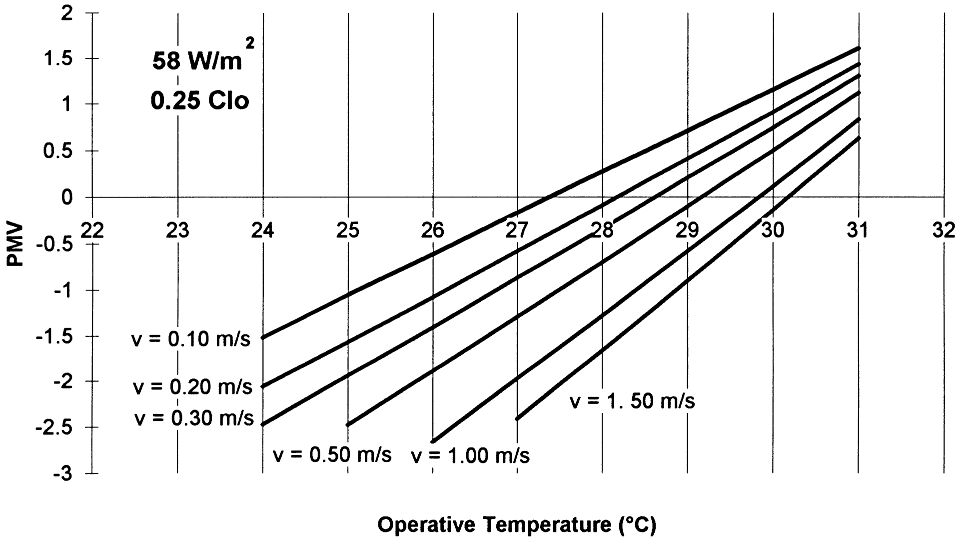
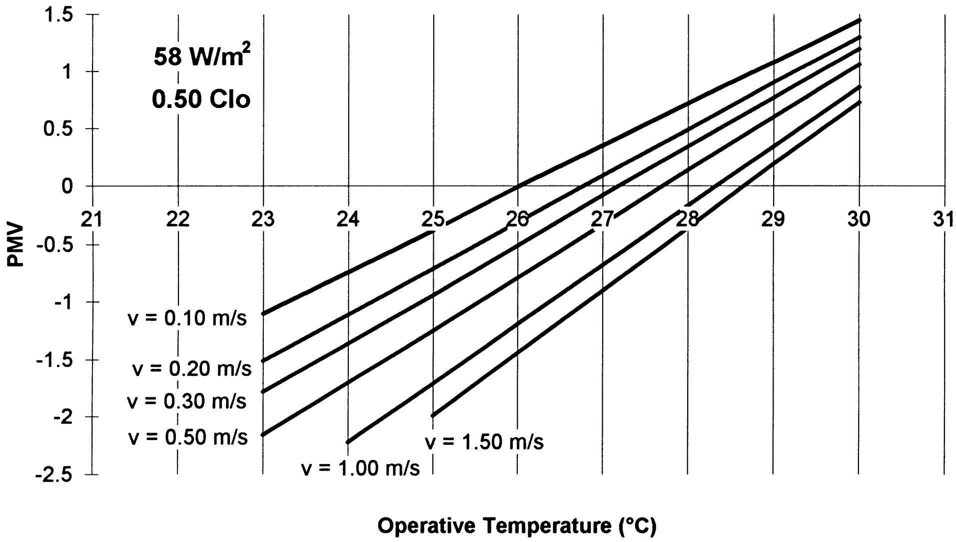



Fig. B1



58 W/m²
0.25 Clo
PMV
v = 0.10 m/s
v = 0.20 m/s
v = 0.30 m/s
v = 0.50 m/s
v = 1.00 m/s
v = 1. 50 m/s
Operative Temperature (°C)


Fig. B2



58 W/m²
0.50 Clo
PMV
v = 0.10 m/s
v = 0.20 m/s
v = 0.30 m/s
v = 0.50 m/s
v = 1.00 m/s
v = 1.50 m/s
Operative Temperature (°C)


Fig. B3

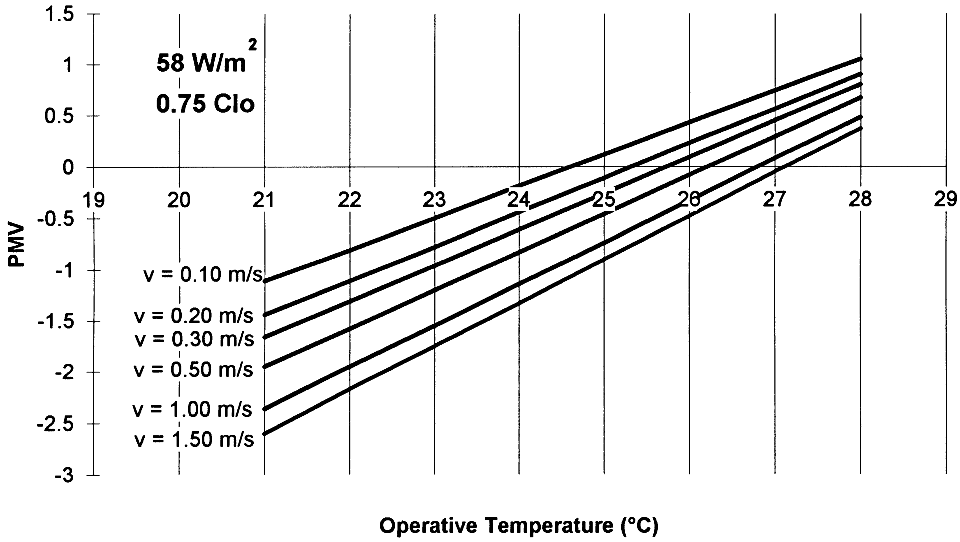

58 W/m²
0.75 Clo
PMV
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
19
20
21
22
23
24
25
26
27
28
29
v = 0.10 m/s
v = 0.20 m/s
v = 0.30 m/s
v = 0.50 m/s
v = 1.00 m/s
v = 1.50 m/s
Operative Temperature (°C)

Fig. B4

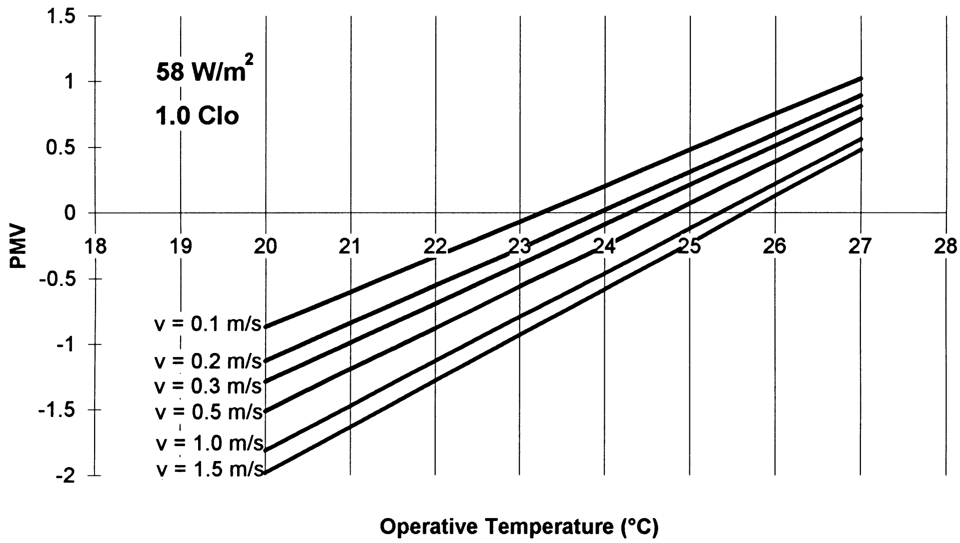

58 W/m²
1.0 Clo
PMV
1.5
1
0.5
0
-0.5
-1
-1.5
-2
18
19
20
21
22
23
24
25
26
27
28
v = 0.1 m/s
v = 0.2 m/s
v = 0.3 m/s
v = 0.5 m/s
v = 1.0 m/s
v = 1.5 m/s
Operative Temperature (°C)

Fig. B5

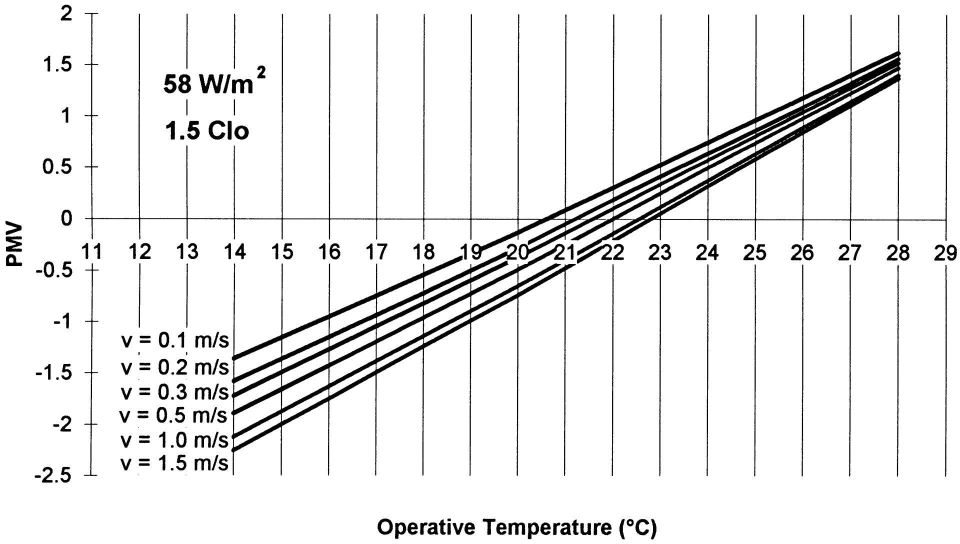

58 W/m2
1.5 Clo
v = 0.1 m/s
v = 0.2 m/s
v = 0.3 m/s
v = 0.5 m/s
v = 1.0 m/s
v = 1.5 m/s
PMV
Operative Temperature (°C)

Fig. B6

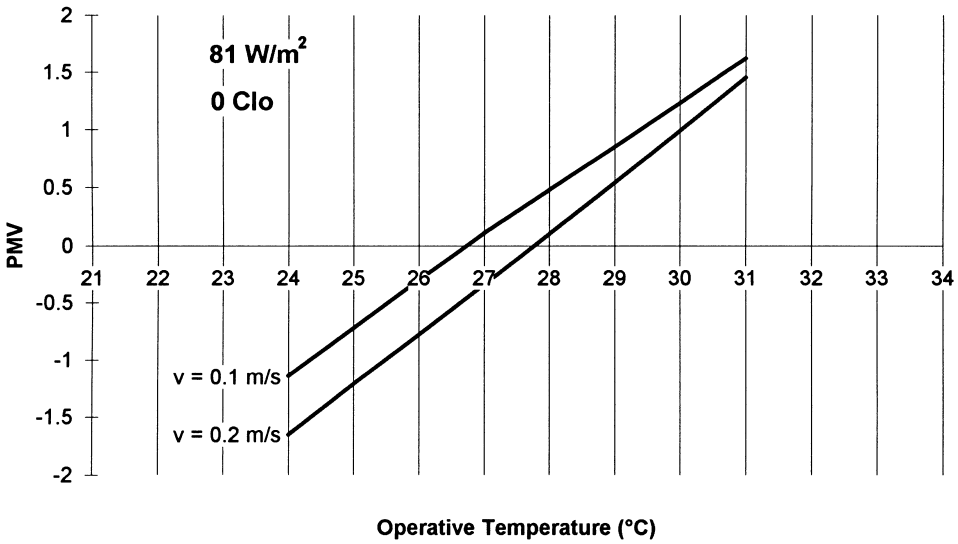

81 W/m2
0 Clo
v = 0.1 m/s
v = 0.2 m/s
PMV
Operative Temperature (°C)

Fig. B7

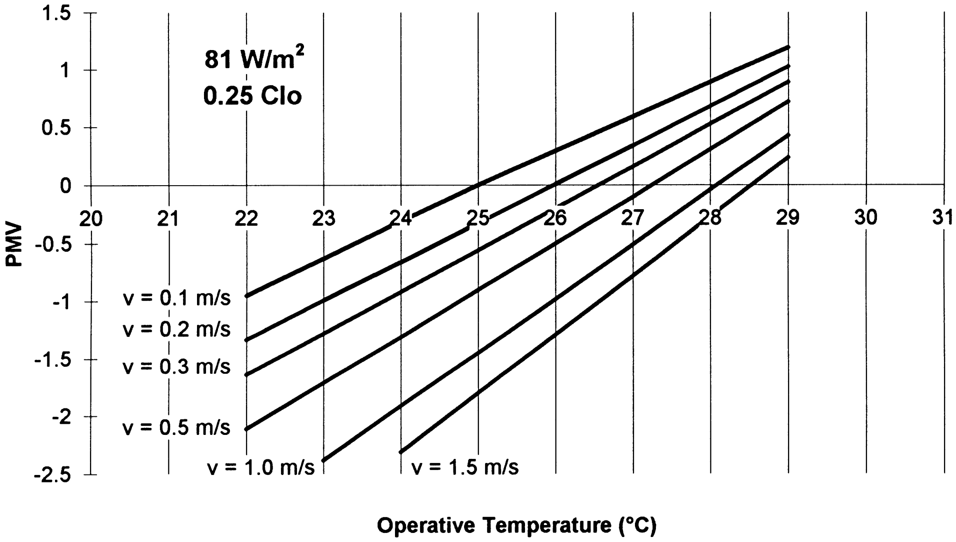

81 W/m2
0.25 Clo
PMV
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
20 21 22 23 24 25 26 27 28 29 30 31
v = 0.1 m/s
v = 0.2 m/s
v = 0.3 m/s
v = 0.5 m/s
v = 1.0 m/s
v = 1.5 m/s
Operative Temperature (°C)

Fig. B8

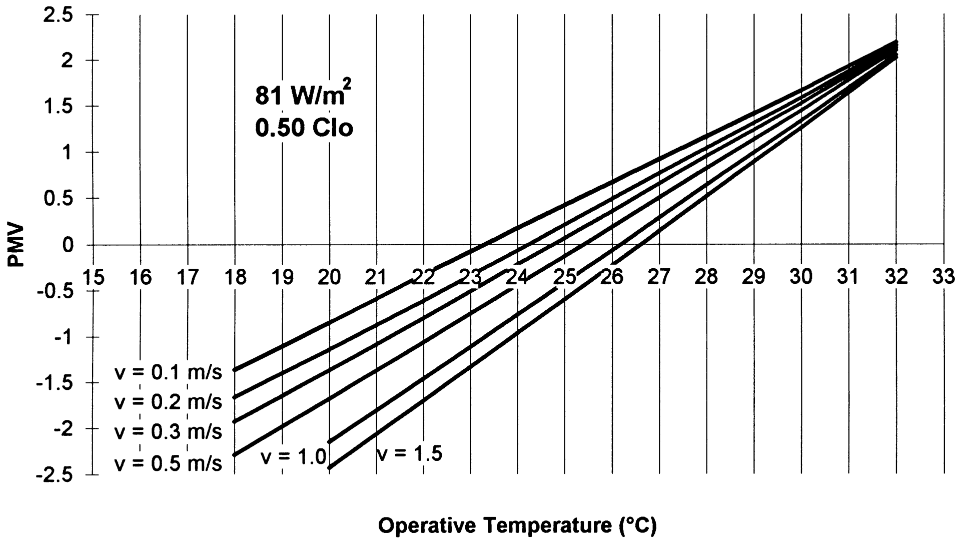

81 W/m2
0.50 Clo
PMV
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
v = 0.1 m/s
v = 0.2 m/s
v = 0.3 m/s
v = 0.5 m/s
v = 1.0
v = 1.5
Operative Temperature (°C)

Fig. B9

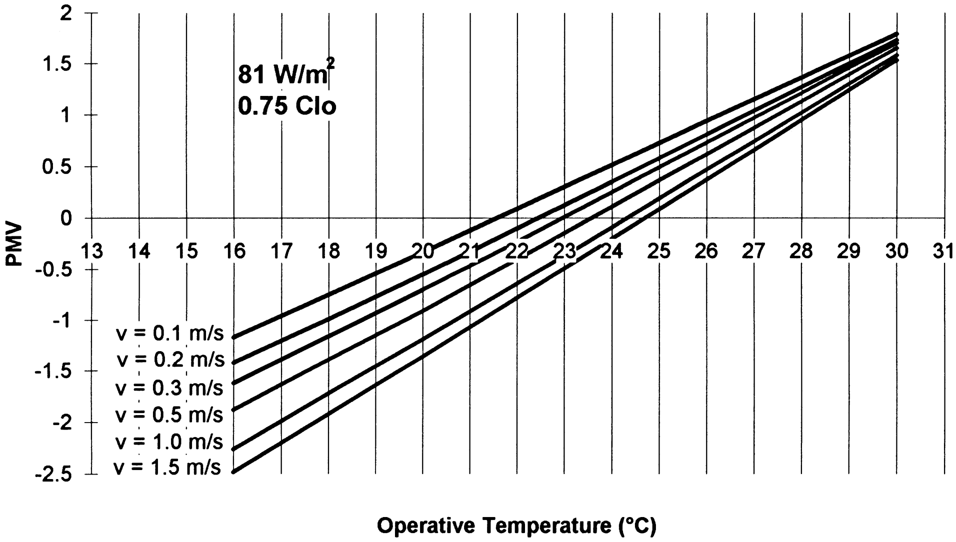



Fig. B10

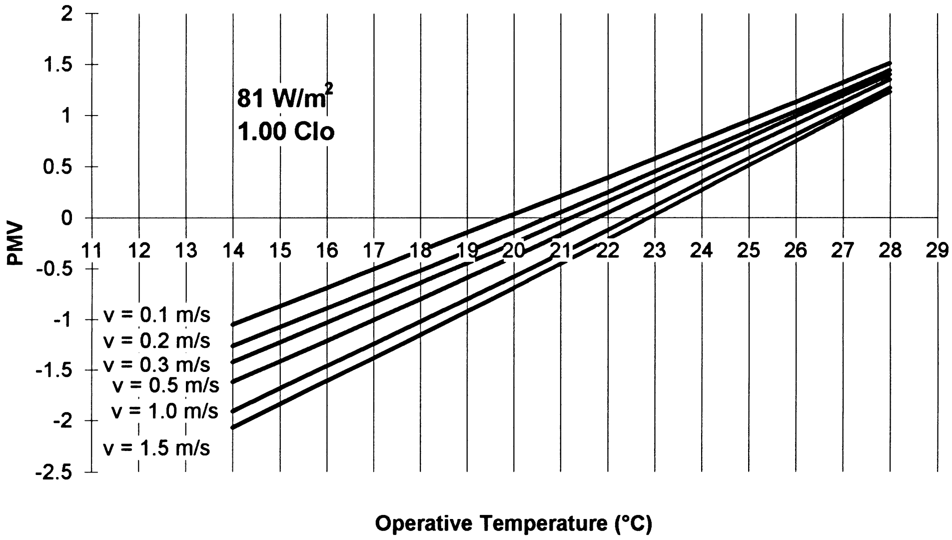



Fig. B11

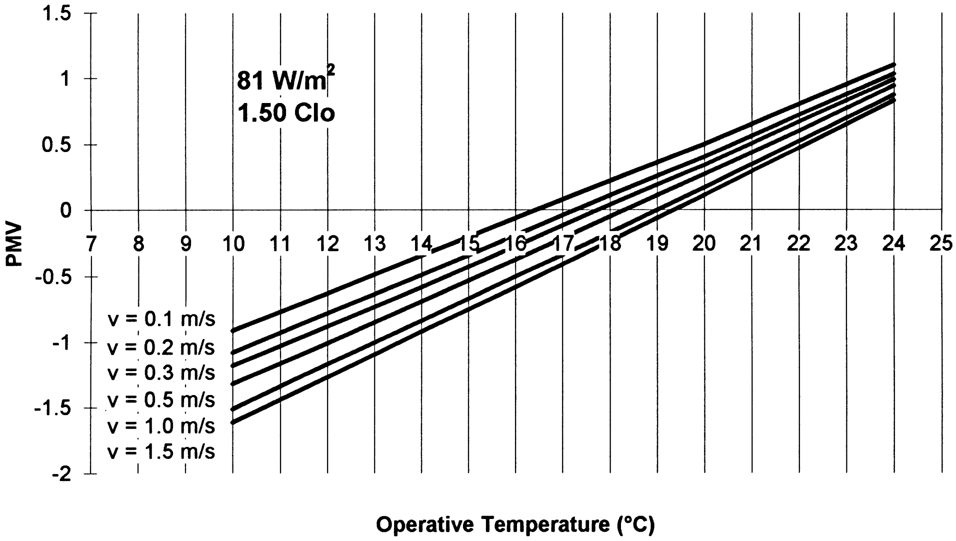



Fig. B12

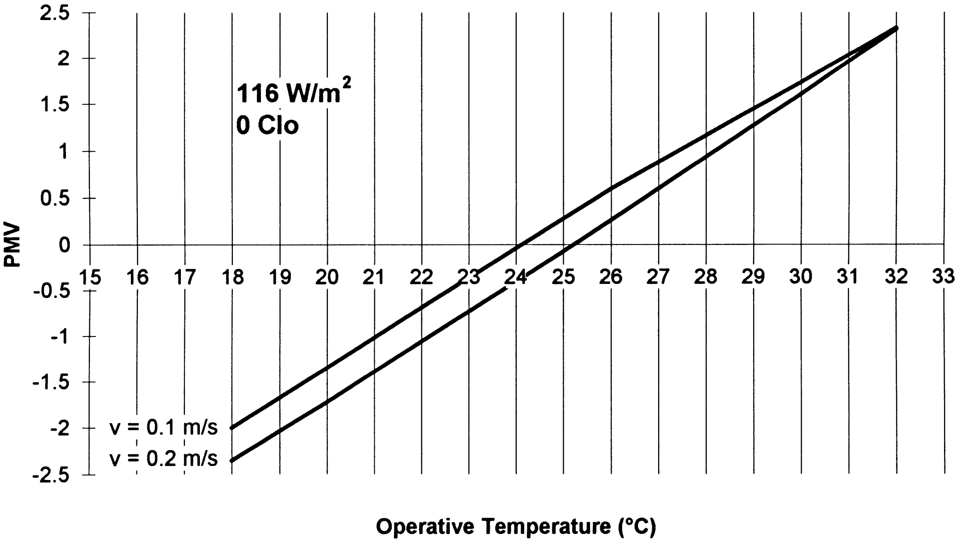



Fig. B13

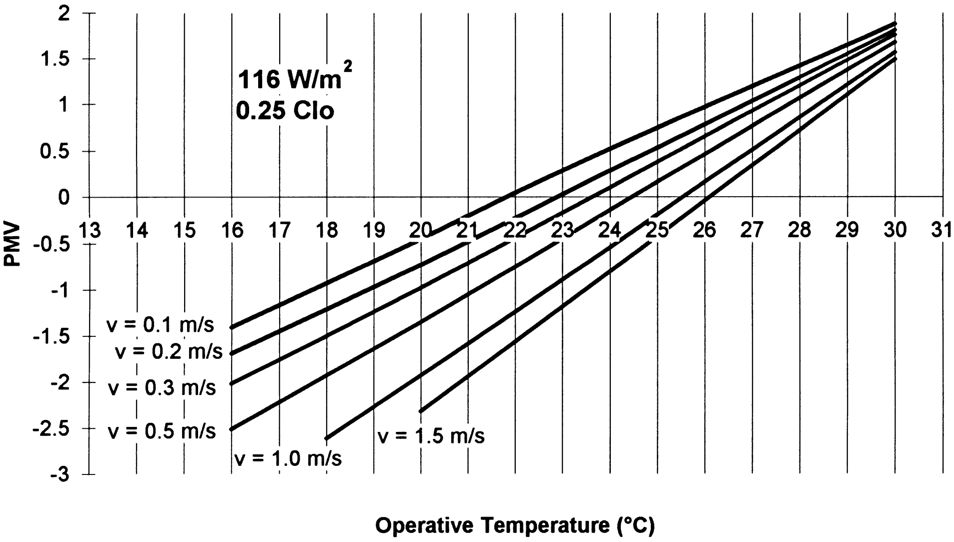



Fig. B14

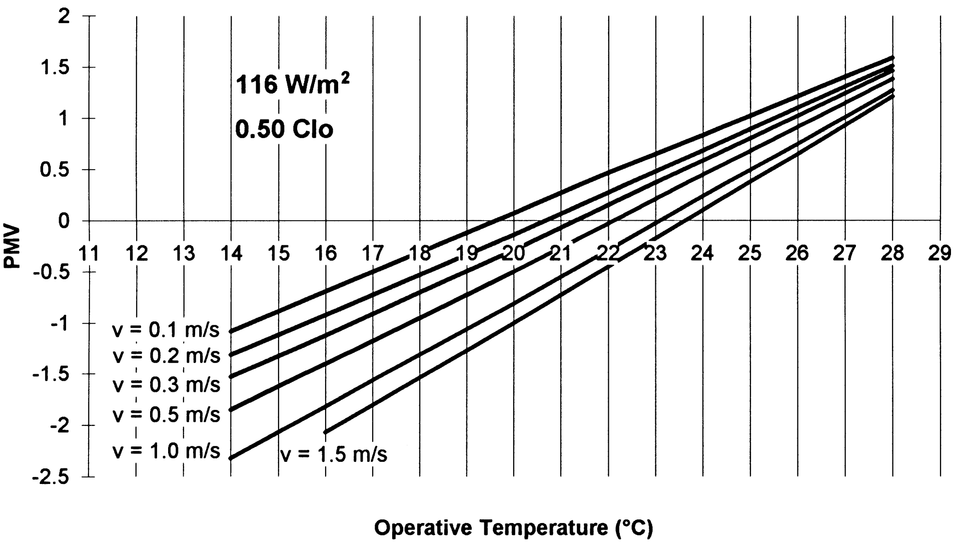



Fig. B15

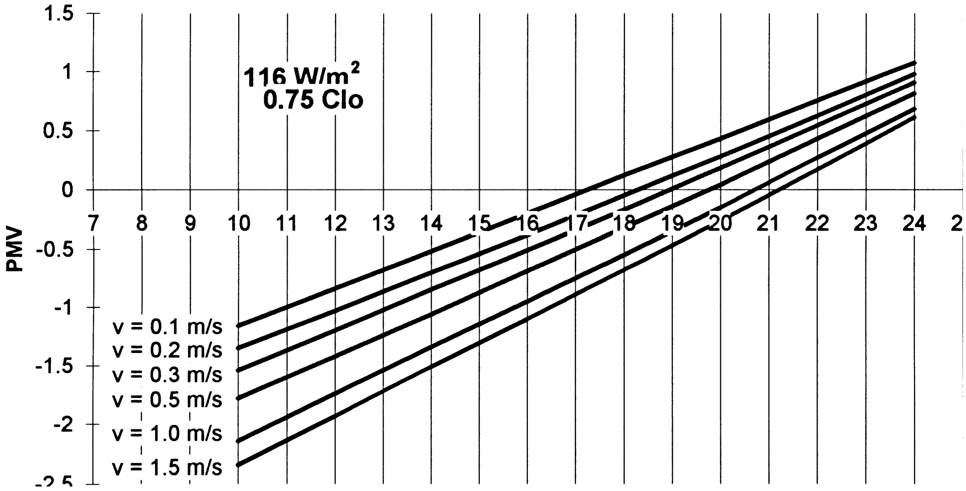



Fig. B16

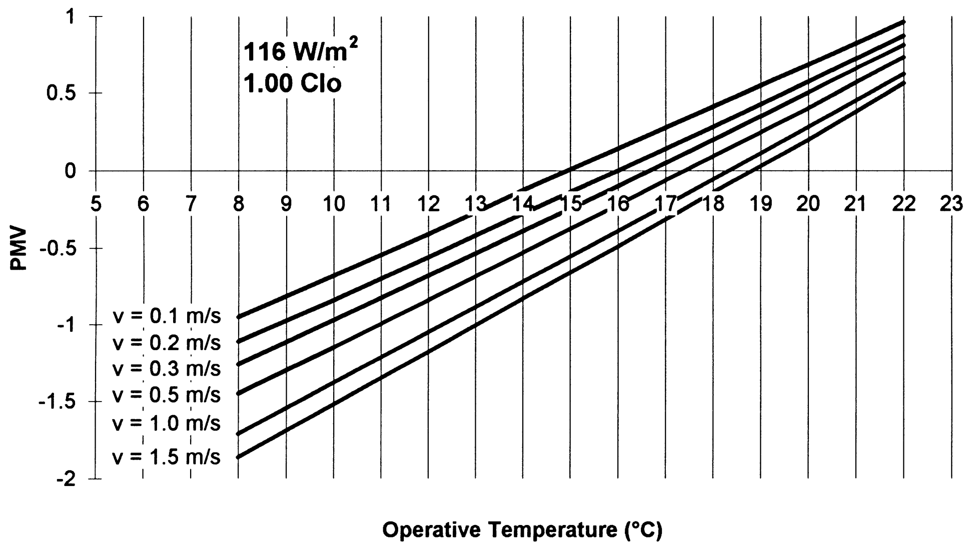



Fig. B17

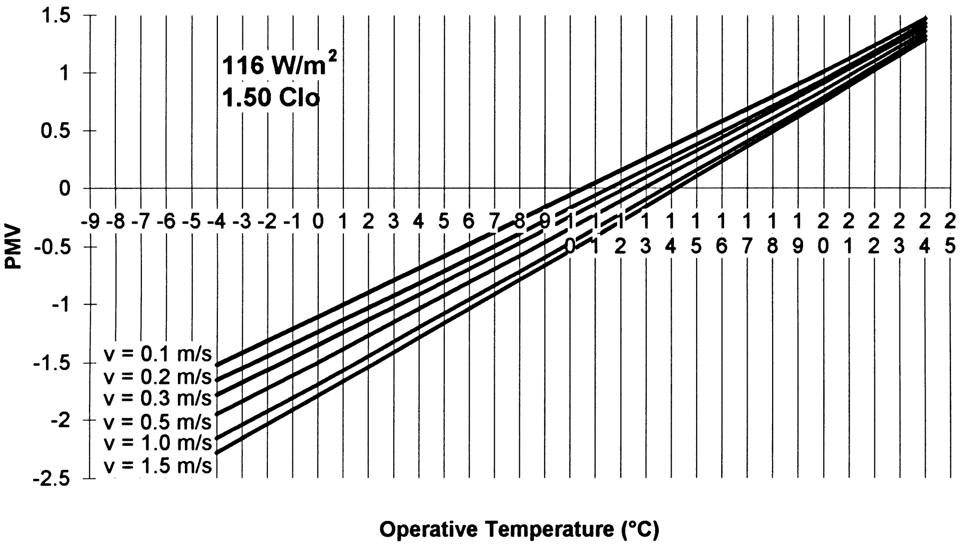



Fig. B18

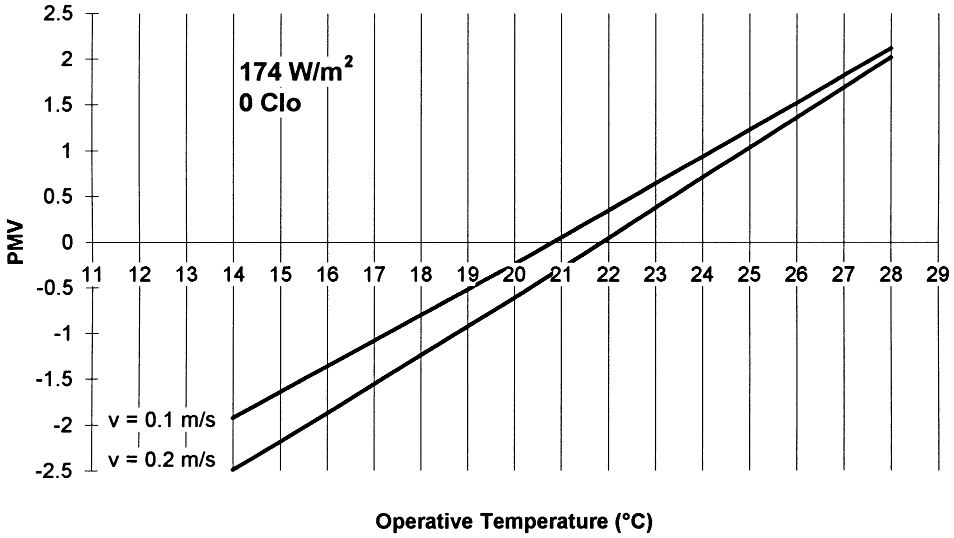



Fig. B19

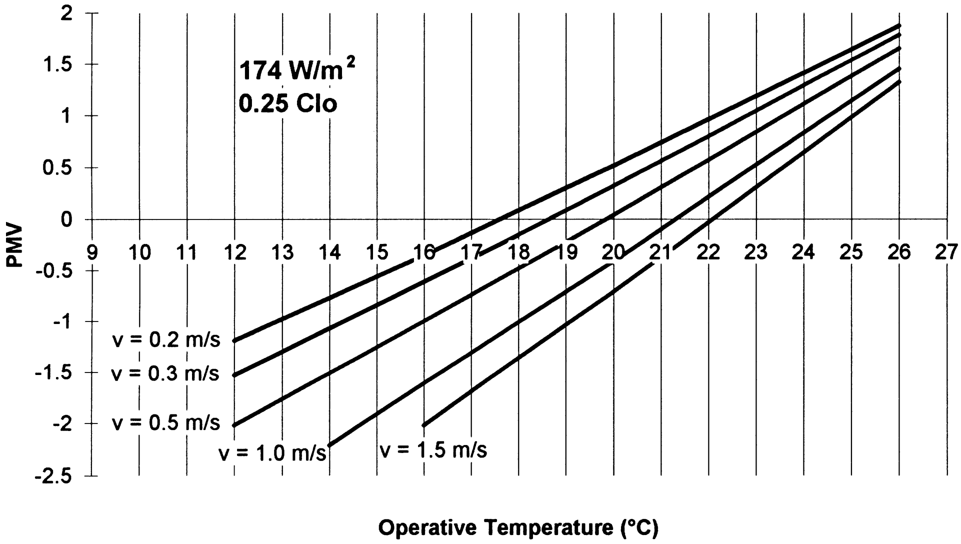



Fig. B20

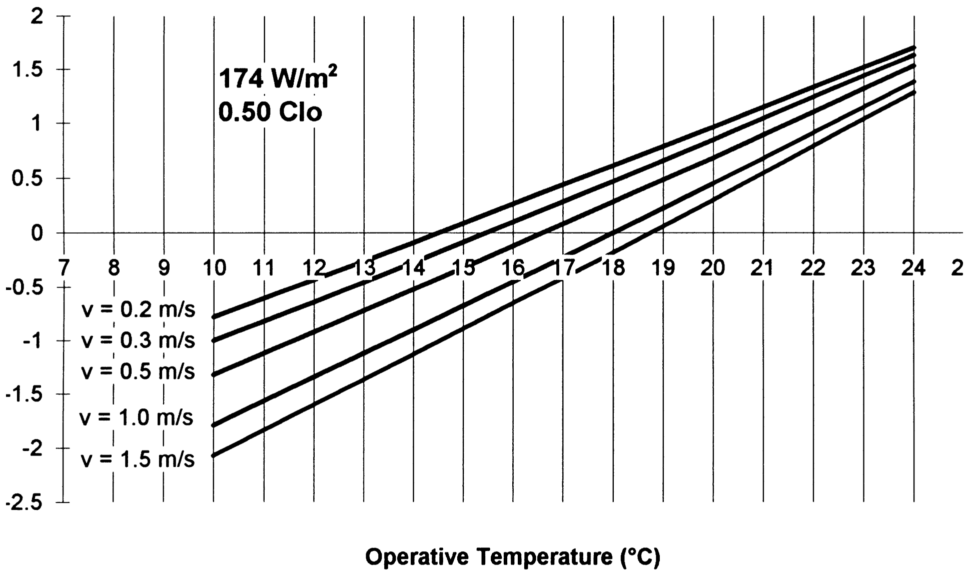



Fig. B21

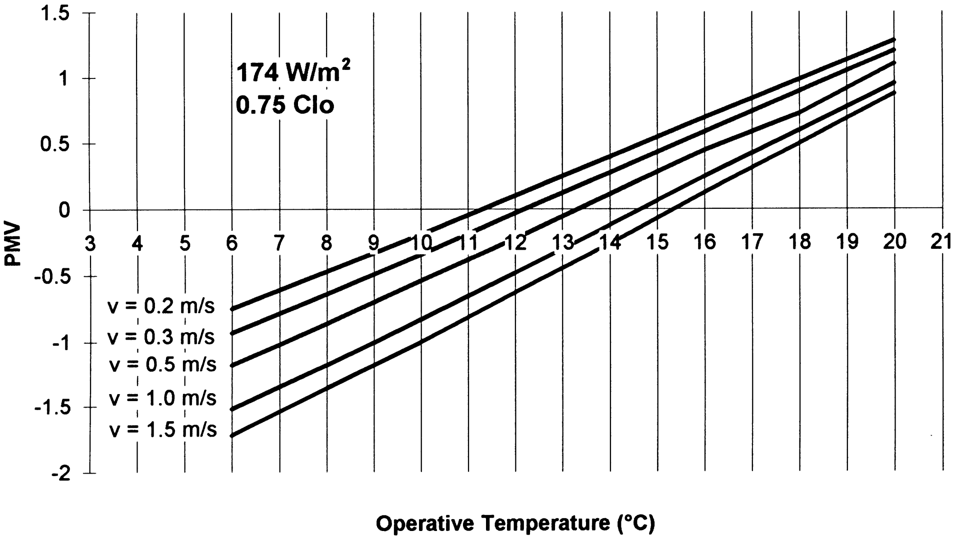



Fig. B22

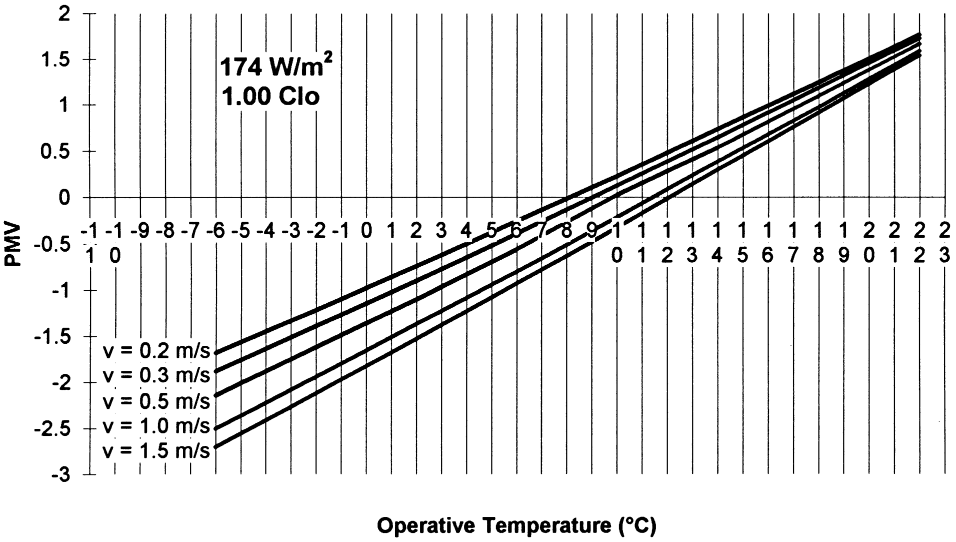



Fig. B23

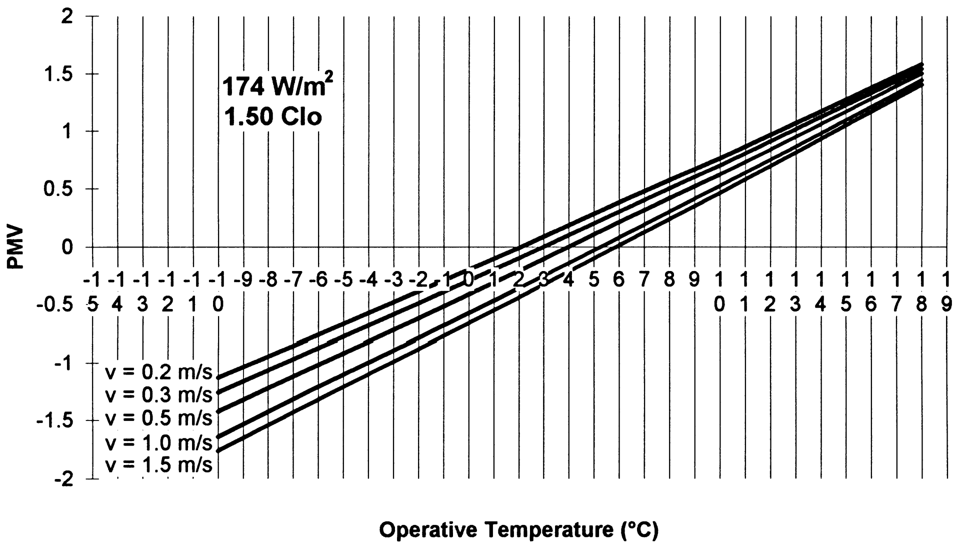



Fig. B24

## References

[1] Fanger PO. Thermal comfort. McGraw-Hill, 1970.

[2] International Standard ISO 7730. Moderate thermal environments—Determination of the *PMV* and *PPD* indices and Specifications of the conditions of thermal comfort, 1984.